Imbedding nonlocality in a relativistic chronology

Antoine Suarez*

Center for Quantum Philosophy, P.O. Box 304, CH-8044 Zurich, Switzerland

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Abstract: An alternative description imbedding nonlocality in a relativistic chronology is proposed. It is argued that vindication of Quantum Mechanics in experiments with moving beam-splitters would mean that there is no real time ordering behind the nonlocal correlations

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The relationship between Quantum Mechanics and Relativity has been object of vast analysis since John Bell showed that: a) if one only admits relativistic local causality (causal links with $v \leq c$), the correlations occurring in two-particle experiments should fulfill clear locality conditions ("Bell's inequalities"), and b) for these experiments Quantum Mechanics bears predictions violating such locality criteria ("Bell's theorem") [1]. Bell-type experiments conducted in the past two decades, in spite of their loopholes, suggest a violation of local causality: statistical correlations are found in space-like separated detections; violation of Bell's inequalities ensure that these correlations are not pre-determined by local events. Nature seems to behave nonlocally, and Quantum Mechanics predicts well the observed distributions. Nevertheless, nonlocality ("Bell influences") cannot be used for faster-than-light communication.

Nonlocal correlations cannot just appear by chance: they require an ordering of the events, causality in some sense. But we use to think about causality as related to some temporal sequence. Therefore, also taking nonlocality for granted, the important question remains: is there a time ordering behind the nonlocal correlations?

Bohm's theory proposes to imbed Quantum Mechanics in a preferred frame or absolute time, in which one event is caused by some earlier event [2]. The theory does not make predictions conflicting with Quantum Mechanics but is rather a particular interpretation of it. However, it does not tell us how to trace this frame [1], so that one sees no mean to decide whether the bohmian "quantum ether" has any physical reality at all.

Recent work shows that it is possible to imbed nonlocality in a real relativistic time ordering, providing one gives up Quantum Mechanics in a new type of experiments involving moving devices. This happens within Multisimultaneity, a nonlocal description using many frames to establish the cause-effect links [3, 4]. More specifically these frames are supposed to be those of the

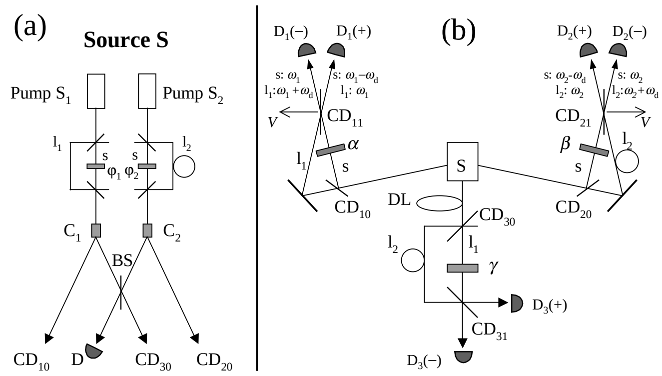

Figure 1: (a) Diagram of the source S used in the experiment. (b) 3-particle experiment using moving choice-devices CD_{11} and CD_{21}. See text for detailed description.

beam-splitters ("choice-devices") [5]. Within each frame the links always correspond to a well defined chronology, one event never depending on some future event. Multisimultaneity has already been developed in the context of 2-particle experiments with moving beam-splitters. In this article we implement it in 3-particle ones, and discuss the meaning of a possible vindication of Quantum Mechanics in tests using moving beam-splitters.

In Fig. 1 (a) is sketched the schema of a source S capable of producing maximally energy-time entangled photon triplets [6]. Photons coming from the pulsed pump laser S_1 reach the nonlinear crystal C_1 either by path l_1 or path s, and those from the pulsed pump S_2 reach the nonlinear crystal C_2 either by l_2 or s. At C_1 and C_2 twin-photons are created by parametric down-conversion. Two output beams, one of C_1 and one of C_2, are directly guided to the beam-splitters CD_{10}, respectively CD_{20}, and as represented in Fig. 1 (b) illuminate two interferometers which use moving choice-devices CD_{11} and CD_{21}. The other two beams are led to interfere into beam-splitter BS. One of the output ports of BS is monitored by detector D, and the photons leaving by the other are guided to beam-splitter CD_{30} and, as represented in Fig. 1 (b), illuminate a third interferometer using a resting beam-splitter CD_{31}. The location of this device can be adjusted by means of delay line DL.

All CD_{il} ($i \in \{1, 2, 3\}, l \in \{0, 1\}$) are assumed to be 50-50 beam-splitters. The two output ports of each CD_{i1} are monitored by detectors $D_i(\sigma)$ ($\sigma \in \{+, -\}$). The short arms of the two interferometers within the source

*suarez@leman.ch

S, and the short arms of the interferometers 1 and 2, are all of them supposed to be equal in length. The arms l_1 and l_2 of interferometer 3 are equal to the arms l_1 respectively l_2 within the source S. The phase parameters are labeled φ_1, φ_2, α, β, and γ.

We consider only the cases in which detector D registers a photon traveling by one of the short arms, and there is one photon in each of the three output ports leading to CD_{10}, CD_{20}, CD_{30}. We assume the pumps S_1 and S_2 to work well synchronized so that the detected photon triplets signals in $D_i(\sigma)$ will exhibit the same time difference for the paths $(S_1sl_1, S_2l_2s, S_2l_2l_1)$ and $(S_1l_1s, S_2sl_2, S_1l_1l_2)$, where the first path expression denotes that: photon 1 comes from pump S_1, travels path s within the source, and then l_1 in interferometer 1; photon 2 comes from pump S_2, travels first path s within the source, and then l_2 in interferometer 2; photon 3 comes from pump S_2, travels path l_2 within the source, and then l_1 of interferometer 3; and the second path expression has a similar meaning [6]. Because of the movement of CD_{11} and CD_{21} the frequency of the reflected photons is Doppler-shifted by an amount ω_d, but the setup in Fig. 1 (b) is arranged so that the total frequency shift for each of the two paths is the same. Therefore detection of the triplets traveling the paths $(S_1sl_1, S_2l_2s, S_2l_2l_1)$ and $(S_1l_1s, S_2sl_2, S_1l_1l_2)$ will exhibit interferences.

According to Quantum Mechanics, beyond the devices CD_{10}, CD_{20} and CD_{30} the three particles are in a GHZ-state of the form:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|S_1sl_1\rangle|S_2l_2s\rangle|S_2l_2l_1\rangle + e^{\phi}|S_1l_1s\rangle|S_2sl_2\rangle|S_1l_1l_2\rangle) \quad (1)$$

where ϕ is a phase factor.

Independently of any timing it holds that:

$$\begin{aligned} Pr^{QM}(\rho,\sigma,\omega) = \frac{1}{K}&|A(S_1sl_1\rho, S_2l_2s\sigma, S_2l_2l_1\omega) \\ &+ A(S_1l_1s\rho, S_2sl_2\sigma, S_1l_1l_2\omega)|^2 \end{aligned} \quad (2)$$

where $P^{QM}(\rho,\sigma,\omega)$ denotes the joint probability of getting the outcome $D_1(\rho)$, $D_2(\sigma)$, $D_2(\omega)$; $A(path\,\rho, path\,\sigma, path\,\omega)$ the corresponding probability amplitudes for the paths and outcome triplets specified within the parentheses; and K is a normalization factor.

Substituting the amplitudes into Eq. (2) yields the following values for the conventional joint probabilities:

$$Pr^{QM}(\rho,\sigma,\omega) = \frac{1}{8}[1+\rho\sigma\omega\,\sin(\alpha-\beta-\gamma+\varphi_2-\varphi_1)] \quad (3)$$

Eq. (3) yields the following correlation coefficient:

$$\begin{aligned} E^{QM} &= \frac{\sum_{\rho,\,\sigma,\,\omega}\rho\sigma\omega\,P^{QM}(\sigma,\omega)}{\sum_{\rho,\,\sigma,\,\omega}P^{QM}(\rho,\sigma,\omega)} \\ &= \sin(\alpha-\beta-\gamma+\varphi_2-\varphi_1) \end{aligned} \quad (4)$$

We implement now the principles and rules of Multisimultaneity [4] in the context of 3-particle experiments.

We denote T_{i1} the time at which the choice between reflection and transmission occurs at device CD_{i1} [5]. In expressions like $(T_{i1} < T_{j1})_{i1}$ the subscript $i1$ after the parenthesis denotes that all times within the parentheses are measured in the inertial frame defined through the velocity of choice-device CD_{i1} at the instant of the choice in this device. If it holds that $(T_{i1} < T_{j1})_{i1}$ and $(T_{i1} < T_{k1})_{i1}$, for $(i,j,k \in \{1,2,3\}, i \neq j \neq k)$, the choice at CD_{i1} is said to occur with "before" timing, and labeled b_{i1}. If it holds that $(T_{j1} > T_{i1} \geq T_{k1})_{i1}$, the choice at CD_{i1} is said to occur with "after" timing with relation to the choice at CD_{k1}, and labeled $a_{i1[k1]}$. If it holds that $(T_{i1} \geq T_{j1})_{i1}$ and $(T_{i1} \geq T_{k1})_{i1}$, the choice at CD_{i1} is said to occur with "after" timing with relation to CD_{j1} and CD_{k1}, or simply with after timing, and labeled a_{i1}. A before-choice at CD_{i1} carrying out the value ρ is denoted $b_{i\,\rho}$, and an after-choice at CD_i carrying out the value ρ is denoted $a_{i\,\rho}$.

The main *Principles* of Multisimultaneity are the following two:

Principle 1: The values $b_{i1\,\rho}$ of particle i do not depend on the values the other particles may produce.

Principle 2: The values $a_{i1\,\rho}$ involve nonlocal causal links, and depend on the values the other particles may produce.

Regarding *Principle 2*, in after-after timings it would obviously be absurd to assume together that $a_{i1\,\rho}$ depends on $a_{j1\,\sigma}$, and $a_{j1\,\sigma}$ on $a_{i1\,\rho}$. Therefore we assume that the outcomes particle i produces in after choices at CD_{i1} do not depend on the outcomes the other particles j and k may actually produce in after choices but on the outcomes they would have produced if the choices at CD_{j1} and CD_{k1} would have been before ones.

We denote $Pr(C)$ the probability that a photon triplet belongs to the class traveling path C, $C \in \{(S_1sl_1, S_2l_2s, S_2l_2l_1), (S_1l_1s, S_2sl_2, S_1l_1l_2)\}$; Expressions like $Pr(b_{i1\,\rho}, a_{j1[i1]\,\sigma}, a_{k1\,\omega})$ denote the probabilities of getting the indicated values. $P(b_{i1\,\rho}|C)$ the conditional probability that photon i leaves CD_{i1} by output port ρ after a before-choice, providing the pair travels path C; expressions as $P(a_{k1\,\omega}|b_{i1\,\rho}, a_{j1[i1]\sigma},)$ mean the conditional probability that photon i leaves CD_{i1} by output port ρ after an after-choice providing photon j would have left CD_{j1} by output port σ in a before-choice, and photon k CD_{k1} by output port ω in an after-choice with relation to CD_{j1}.

The rule to calculate the joint probabilities for the outcomes at CD_{11}, CD_{21} and CD_{31}, with all choices occurring under before timing, follows straightforwardly from *Principle 1* above, and is given by the expression:

$$\begin{aligned} &Pr(b_{11\,\rho}, b_{21\,\sigma}, b_{31\,\omega}) \\ &= \sum_C Pr(C)\,Pr(b_{11\,\rho}|C)\,Pr(b_{21\,\sigma}|C)\,Pr(b_{31\,\omega}|C) \end{aligned} \quad (5)$$

For the different paths it holds that:

$$Pr(C) = \frac{1}{K}|A(S_1 s l_1, S_2 l_2 s, S_2 l_2 l_1)|^2$$
$$= \frac{1}{K}|A(S_1 l_1 s, S_2 s l_2, S_1 l_1 l_2)|^2 = \frac{1}{2} \qquad (6)$$

And for the $b_{i1\,\rho}$ values, $i \in \{1,2,3\}$, $\rho \in \{+,-\}$, one is led to the following relations:

$$Pr(b_{i1\,\rho}|C) = |A(s\,\rho)|^2 = |A(l_1\,\rho)|^2 = |A(l_2\,\rho)|^2 = \frac{1}{2} \qquad (7)$$

Substituting (6) and (7) into (5) yields:

$$Pr(b_{11\,\rho}, b_{21\,\sigma}, b_{31\,\omega}) = \frac{1}{8} \qquad (8)$$

For each choice-device with input ports $(p,q) \in \{(l_1,s),(l_2,s),(l_1,l_2)\}$ and output ports $(+,-)$, the path amplitudes fulfill the relation:

$$A(p+)A^*(q+) + A(p-)A^*(q-) = 0 \qquad (9)$$

Relation (9) implies that:

$$\sum_\omega Pr^{QM}(\rho,\sigma,\omega)$$
$$= \sum_\omega |A(S_1 s l_1\rho, S_2 l_2 s\sigma, S_2 l_2 l_1\omega) + A(S_1 l_1 s\rho, S_2 s l_2\sigma, S_1 l_1 l_2\omega)|^2$$
$$= |C|^2|A(l_1\rho)|^2|A(s\sigma)|^2 + |C|^2|A(s\rho)|^2|A(l_2\sigma)|^2$$
$$= \sum_C Pr(C)\,Pr(b_{i1\,\rho}|C)\,Pr(b_{j1\,\sigma}|C) = Pr(b_{i1\,\rho}, b_{j1\,\sigma}) \qquad (10)$$

and similar equalities for summations over ρ and σ.

Relation (10) means that for the experiment we are considering the quantum mechanical marginals can be described as though the involved choices would be before ones, i.e. the values $a_{i1[k1]\,\rho}$ behave as $b_{i1\,\rho}$ ones.

Consider *first* the type of timing that practically result when all choice-devices are at rest, i.e. $(b_{i1\,\rho}, a_{j1[i1]\,\sigma}, a_{k1\,\omega})$. For these timings we assume that Multisimultaneity reproduces the predictions of Quantum Mechanics, so that:

$$Pr(b_{i1\,\rho}, a_{j1[i1]\,\sigma}, a_{k1\,\omega}) = Pr^{QM}(\rho,\sigma,\omega) \qquad (11)$$

From *Principle 2* above it follows that:

$$Pr(b_{i1\,\rho}, a_{j1[i1]\,\sigma}, a_{k1\,\omega})$$
$$= \sum_C P(C)\,P(b_{i1\,\rho}|C)\,P(a_{j1\,\sigma}|b_{i1\,\rho})\,P(a_{k1\,\omega}|b_{i1\,\rho}, a_{j1[i1]\,\sigma}) \qquad (12)$$

Summing over ω in (12), and taking account of (11) and (10) one is led to:

$$\sum_\omega Pr(b_{i1\,\rho}, a_{j1[i1]\,\sigma}, a_{k1\,\omega}) = \sum_\omega Pr^{QM}(\rho,\sigma,\omega)$$
$$= \sum_C P(C)\,P(b_{i1\,\rho}|C)\,P(A_{j1\,\sigma}|b_{i1\,\rho})$$
$$= \sum_C P(C)\,P(b_{i1\,\rho}|C)\,P(b_{j1\,\sigma}|C) \qquad (13)$$

From (12) and (13) it follows that:

$$Pr(a_{k1\,\omega}|b_{i1\,\rho}, a_{j1[i1]\,\sigma}) = Pr(a_{k1\,\omega}|b_{i1\,\rho}, b_{j1\,\sigma})$$
$$= \frac{Pr^{QM}(\rho,\sigma,\omega)}{\sum_\omega Pr^{QM}(\rho,\sigma,\omega)}$$
$$= \frac{1}{2}[1 + \rho\sigma\omega\,\sin(\alpha - \beta - \gamma + \varphi_2 - \varphi_1)] \qquad (14)$$

Since by setting CD_{j1} in movement one could change instantaneously the timing $(b_{i1}, a_{j1[i1]}, a_{k1})$ into (b_{i1}, b_{j1}, a_{k1}), property (10) prevents that this action can be used to produce superluminal signaling. For experiments that don't fulfill (10) Multisimultaneity can be conveniently completed so that superluminal signaling remains forbidden.

Consider *secondly* the experiment of Fig. 1 (b) conducted with timing $(a_{11[31]}, a_{21[31]}, b_{31})$. Since as stated above the values $a_{i1[k1]\,\rho}$ behave as $b_{i1\,\rho}$ ones, taking account of (8) one is led to:

$$Pr(a_{11[31]\,\rho}, a_{21[31]\,\sigma}, b_{31\,\omega}) = Pr(b_{11\,\rho}, b_{21\,\sigma}, b_{31\,\omega}) = \frac{1}{8} \qquad (15)$$

And (15) yields the following correlation coefficient:

$$E^{bbb} = \frac{\sum_{\rho,\,\sigma,\,\omega} \rho\sigma\omega\,Pr(b_{11\,\rho}, b_{21\,\sigma}, b_{31\,\omega})}{\sum_{\rho,\,\sigma,\,\omega} Pr(b_{11\,\rho}, b_{21\,\sigma}, b_{31\,\omega})} = 0 \qquad (16)$$

Consider *thirdly* the timing $(a_{11\,\rho}, a_{21\,\sigma}, b_{31\,\omega})$. Applying *Principle 2* one gets:

$$Pr(a_{11\,\rho}, a_{21\,\sigma}, b_{31\,\omega})$$
$$= \sum_{C,\rho',\sigma'} Pr(C)\,Pr(b_{11\,\rho'}|C)\,Pr(b_{21\,\sigma'}|C)Pr(b_{31\,\omega}|C)$$
$$\times\, Pr(a_{11\,\rho}|b_{21\,\sigma'}, b_{31\,\omega})\,Pr(a_{21\,\sigma}|b_{11\,\rho'}, b_{31\,\omega}) \qquad (17)$$

Substituting (6), (7) and (14) into (17) gives:

$$Pr(a_{11\,\rho}, a_{21\,\sigma}, b_{31\,\omega}) = \frac{1}{8} \qquad (18)$$

Eq. (18) yields the following correlation coefficient:

$$E^{aab} = \frac{\sum_{\rho,\,\sigma,\,\omega} \rho\sigma\omega\,Pr(a_{11\,\rho}, a_{21\,\sigma}, b_{31\,\omega})}{\sum_{\rho,\,\sigma,\,\omega} Pr(a_{11\,\rho}, a_{21\,\sigma}, b_{31\,\omega})} = 0 \qquad (19)$$

Consider *finally* the timing $(a_{11\,\rho}, a_{21\,\sigma}, a_{31\,\omega})$. *Principle 2* leads to the following rule:

$$
\begin{aligned}
&Pr(a_{11\,\rho}, a_{21\,\sigma}, a_{31\,\omega}) \\
&= \sum_{C,\rho',\sigma'} Pr(C)\, Pr(b_{11\,\rho'}|C)\, Pr(b_{21\,\sigma'}|C) Pr(b_{31\,\omega'}|C) \\
&\qquad \times Pr(a_{11\,\rho}|b_{21\,\sigma'}, b_{31\,\omega'})\, Pr(a_{21\,\sigma}|b_{11\,\rho'}, b_{31\,\omega'}) \\
&\qquad \times Pr(a_{31\,\sigma}|b_{11\,\rho'}, b_{21\,\sigma'}) \qquad (20)
\end{aligned}
$$

Substituting (6), (7) and (14) into (20) gives:

$$
\begin{aligned}
&Pr(a_{11\,\rho}, a_{21\,\sigma}, a_{31\,\omega}) \\
&= \frac{1}{8}[1 + \rho\sigma\omega\, \sin^3(\alpha - \beta - \gamma + \varphi_2 - \varphi_1)] \qquad (21)
\end{aligned}
$$

Eq. (21) yields the following correlation coefficient:

$$
\begin{aligned}
E^{aaa} &= \frac{\sum_{\rho,\,\sigma,\,\omega} \rho\sigma\omega\, Pr(A_{11\,\rho}, A_{21\,\sigma}, A_{31\,\omega})}{\sum_{\rho,\,\sigma,\,\omega} Pr(A_{11\,\rho}, A_{21\,\sigma}, A_{31\,\omega})} \\
&= \sin^3(\alpha - \beta - \gamma + \varphi_2 - \varphi_1) \qquad (22)
\end{aligned}
$$

The predictions (16) and (19) are quantitatively clearly testable against the prediction (4): while Quantum Mechanics predicts a correlation coefficient E oscillating between 1 and -1 depending on the phase values, Multisimultaneity predicts the constant value $E = 0$.

Real tests are feasible. Before-before and after-after timings require that the difference δt between the optical paths traveled by the two photons, the real distance D between the two choice-devices, and the velocity V defining the inertial frame, fulfill the relation [3]:

$$
D > \frac{c^2 \delta t}{V} \qquad (23)
$$

Working within the laboratory one can achieve an alignment ensuring that $\delta t \approx 2$ ps. Acousto-optic cells make it possible to reach values as $V = 2.5$ km/s [4]. Then, relation (23) yields the following lower limit for the distance D between CD_{11} and CD_{21}:

$$
D > 72\, m \qquad (24)
$$

To have the timing (b_{11}, b_{21}, b_{31}) the direction of movement is that indicated in Fig. 1 (b), and for timing (a_{11}, a_{21}, b_{31}) the reverse, and moreover, in both cases, CD_{31} has to be set so that the arrival of particle 3 at CD_{31} in the laboratory frame occurs before the arrivals of particle 1 and 2 at CD_{11}, respectively CD_{21}.

Regarding the prediction (22), it might be difficult to distinguish it from (4) because the corresponding plots of the experimental data will exhibit quite similar shapes. Nevertheless, assumed the experiment upholds (16) and (19), the interest of testing (22) will of course be that of a further confirmation of Multisimultaneity. Timing (a_{11}, a_{21}, a_{31}) requires the following: to adjust the location of CD_{31} so that the arrival of particle 3 at CD_{31} in the laboratory frame occurs after the arrivals of particle 1 and 2 at CD_{11}, respectively CD_{21}; to reverse the direction of movement indicated in Fig. 1; and to orient CD_{i1}, $i \in \{1, 2\}$ till to get the sound wave propagating towards CD_{31}. Assumed a value of 90^o for the angle CD_{11}-CD_{31}-CD_{21}, and distances CD_{11}-CD_{31}, CD_{21}-CD_{31} of about 72 m, then one has a distance CD_{11}-CD_{21} of 102 m, and velocity components of 1.77 km/s in the direction CD_{11}-CD_{21}, i.e. values which fulfill the condition (23).

In summary, we have shown that a description imbedding nonlocal causality in a relativistic time ordering is possible for experiments involving more than 2 particles.

As far as one aims nonlocal causal descriptions based on relativistic (real) timings, it is natural to assume that each choice involves all (local and nonlocal) information that is available within the inertial frame of the choice-device at the instant the particle arrives. Then the basic principle of any relativistic nonlocal description is the following one: in experiments in which all choices take place under before timing the nonlocal correlations should disappear. By contrast Quantum Mechanics predicts such correlations independently of any timing. Therefore, experiments using only before timings can be considered a criterion allowing us to decide whether or not the nonlocal physical reality can be imbedded into a relativistic chronology.

Prevailing of Quantum Mechanics in forthcoming Bell experiments with moving choice-devices would support the view that the nonlocal correlations are caused independently of any real chronology [7]. In this sense Quantum Mechanics can be considered a causal description which is both *nonlocal* and *nontemporal*.

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